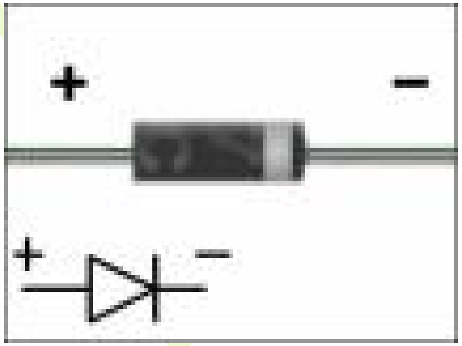
Lecture 02

Diodes



圖片來自;www.personeel.glr.nl/koster/elektro/diodes.JP

topics

- Semiconductor physics
- Diode forward characteristic
- Diode reverse characteristic
- Special diodes

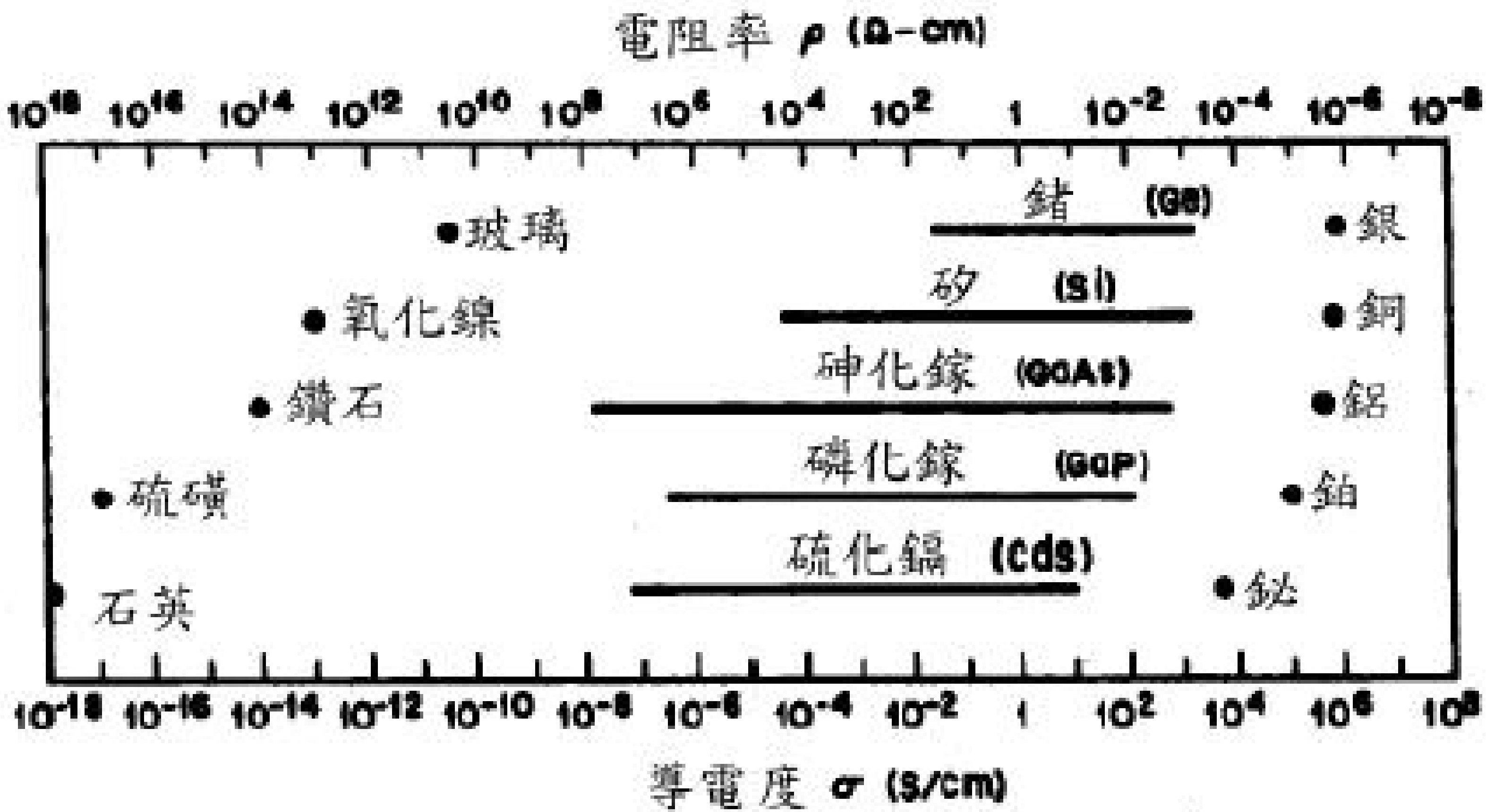
Solid-state material

- Insulator (SiO2)
  - Strong covalent bonds, no free electron
  - Conductivity $\sigma < 10^{-8}(\Omega - cm)^{-1}$
  - Energy gap $Eg \geq 3eV$

$\boxed{1eV \equiv 1.6 \times 10^{-19}\ Joule}$

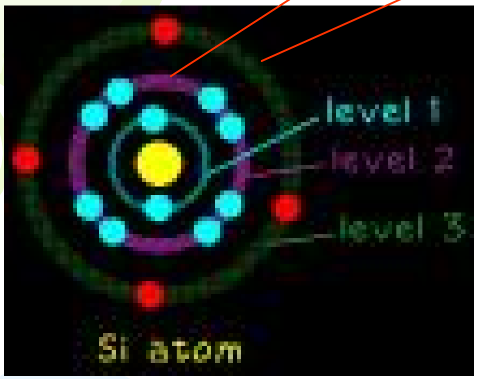
eV: eletron voltage

- Semi-conductor (Si, Ge)
  - Conductivity $10^{-8} < \sigma < 10^{3}(\Omega - cm)^{-1}$
  - Energy gap $0 < Eg < 3eV$
- Conductor (Cu, Ag)
  - Weak covalent bonds, many free electrons
  - Conductivity $\sigma > 10^{3}(\Omega - cm)^{-1}$
  - Energy gap $Eg = 0eV$


電阻率 ρ (Ω-cm)
10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4 10^2 1 10^-2 10^-4 10^-6 10^-8
玻璃
氧化鎳
鑽石
硫磺
石英
鍺 (Ge)
矽 (Si)
砷化鎵 (GaAs)
磷化鎵 (GaP)
硫化鎘 (CdS)
銀
銅
鋁
鉑
鉍
10^-18 10^-16 10^-14 10^-12 10^-10 10^-8 10^-6 10^-4 10^-2 1 10^2 10^4 10^6 10^8
導電度 σ (S/cm)

Energy gap

Energy level



Infinite many atoms

high energy

conduction band

Energy-level gap

valance band

Low energy

http://oldsite.vislab.usyd.edu.au/photonics/devices/semicdev/doping2.html

One atom

Level 3 : high energy

Level 1 : low energy

electrons

conduction band

Energy gap overlap

valance band

conduction band

Energy-level gap

valance band

conduction band

Energy-level gap

valance band

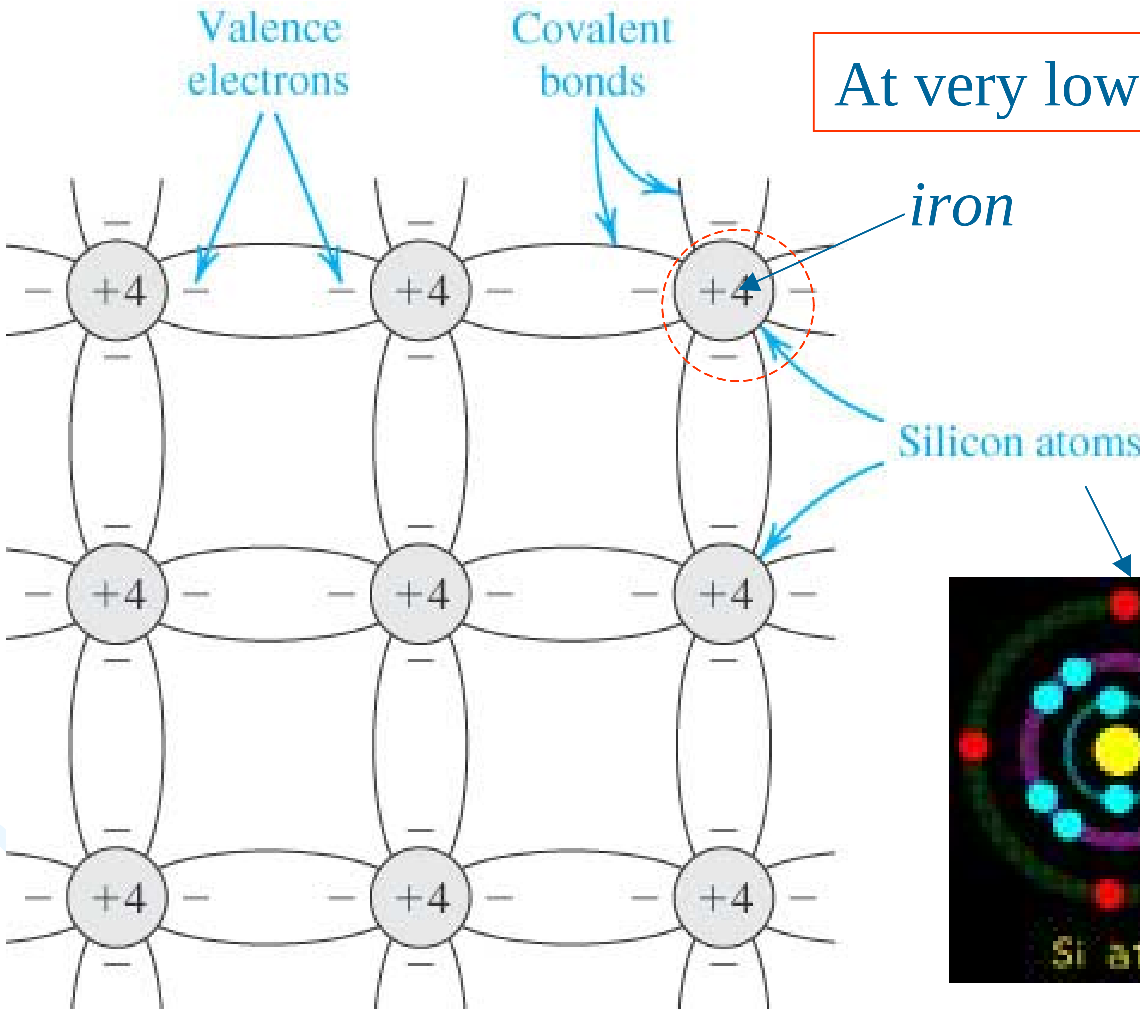
Famous Semi-conductors

- Element semi-conductor
  - Si
    - Cheap
    - Energy gap > Ge → small leakage current
    - Stable oxide
  - Ge
    - First transistor
    - Small energy gap
    - Unstable oxide
- Compound semi-conductor
  - GaAs

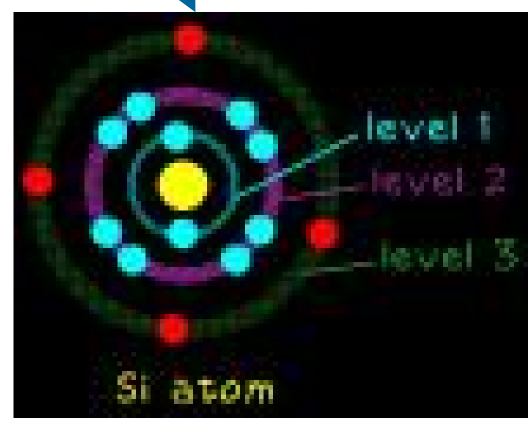
半導體種類	固有電子濃度 n_i (cm^{-3})	帶溝 E_g (eV)
鍺(Ge)	2.4×10^{13}	0.67
矽(Si)	1.45×10^{10}	1.12
砷化鎵(GaAs)	1.79×10^{6}	1.42

Intrinsic semiconductor (silicon)

At very low temperature

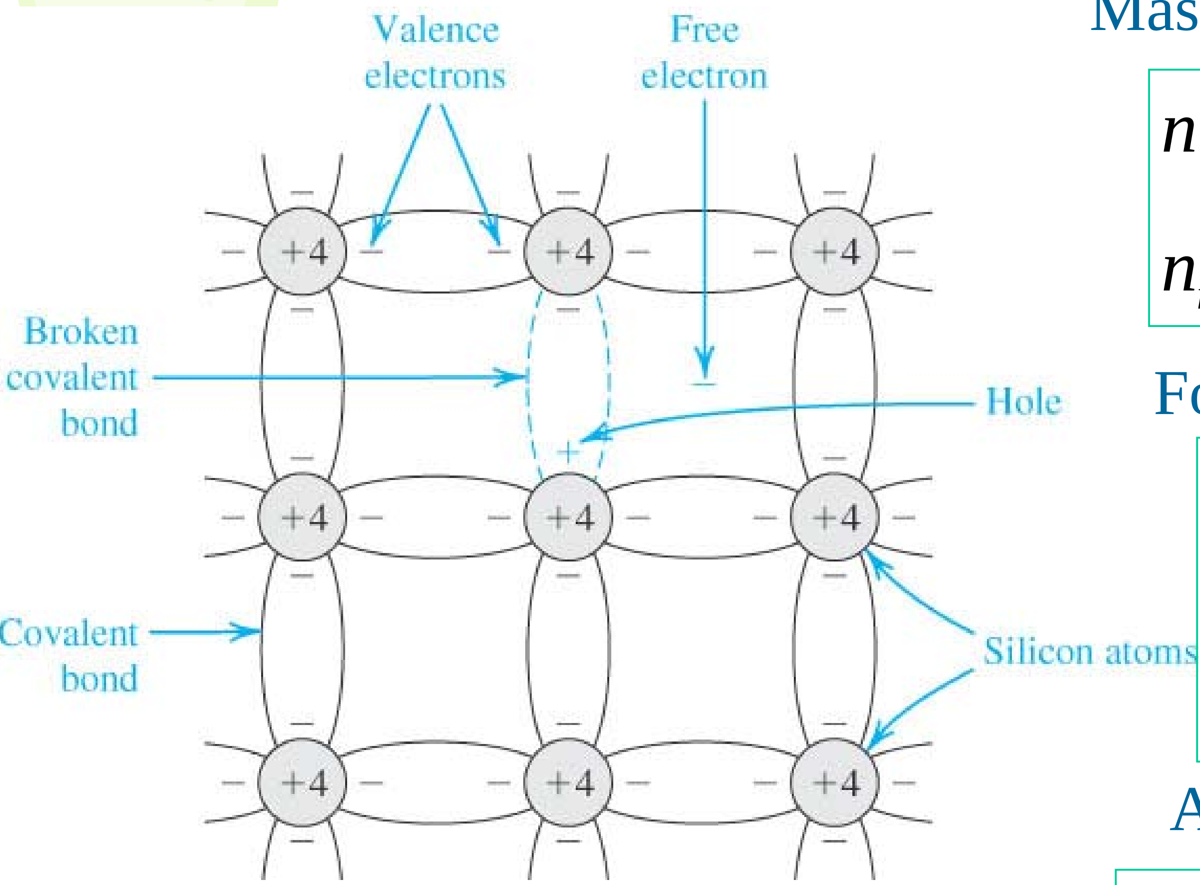


iron



http://oldsite.vislab.usyd.edu.au/photonics/devices/semicdev/doping2.html

Intrinsic semiconductor at room temperature



Free electrons and holes generated by thermal ionization, so the concentration is same $n = p = n_i$

Mass-action law:

$$n = p = n_i \Rightarrow np = n_i^2$$

$$n_i^2 = BT^3 e^{-\frac{E_G}{KT}}$$

For silicon semi-conductor

Material parameter

$$B = 5.4 \times 10^{31}$$

$$E_G = 1.12eV$$

Boltzmann's constant

$$k = 8.62 \times 10^{-5}\ eV/K$$

At room temperature

$$T \approx 300K$$

$$n_i \approx 1.45 \times 10^{10}\ carriers/cm^3$$

Hole and electrons moving

1. drift

E : electric field strength (V/cm) $\quad E = \dfrac{f}{q}$

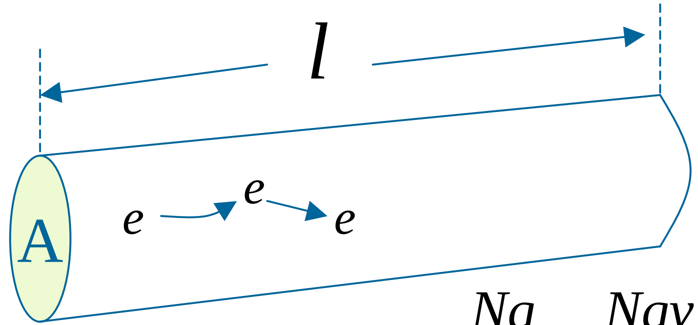
μ : mobility of hole/electron (cm^2/V-sec)

Drift velocity $\quad v = \mu E$

Resistivity $\quad R = \rho \, {}^{l}\!/\!_{A}$

Charge density $\quad \rho \equiv nq(\Omega - cm)$

conductivity $\quad \sigma \equiv nq\mu$



$$I \equiv \frac{Nq}{T} = \frac{Nqv}{L}$$

$$J = \frac{I}{A} \Rightarrow J = \frac{Nqv}{AL}$$

$$n \equiv \frac{N}{LA} \Rightarrow J = nqv$$

Electron density

$$\boxed{J = \sigma E}$$

$$J_p = qp\mu_p E$$

$$J_n = qn\mu_n E$$

$$J_{drift} = q(p\mu_p + n\mu_n)E$$

For intrinsic silicon :

$$\mu_p = 480 \, {}^{cm^2}\!/\!_{V \cdot s}$$

$$\mu_n = 1350 \, {}^{cm^2}\!/\!_{V \cdot s}$$

2. diffusion

$$J_p = -qD_p \frac{dp}{dx}$$

$$J_n = qD_n \frac{dn}{dx}$$

$$q = 1.6 \times 10^{-19} C$$

J : current density

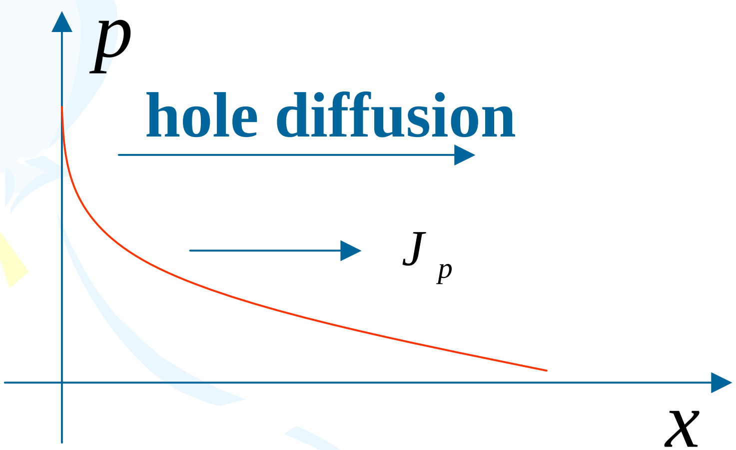
q : electron charge

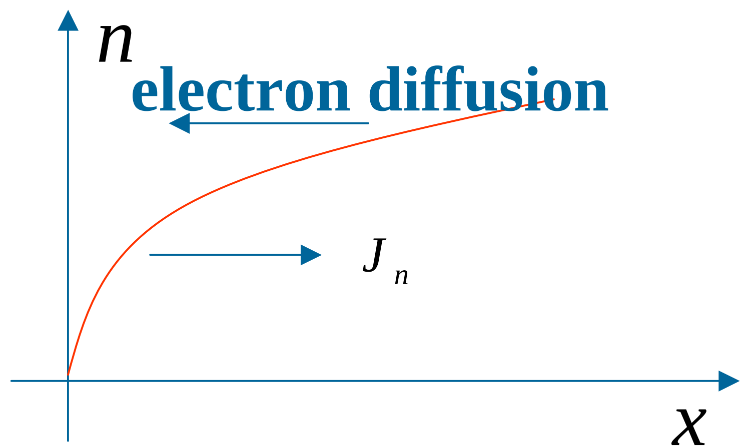
D : diffusivity of hole/electron

For intrinsic silicon :

$$D_p = 12 \, cm^2/s$$

$$D_n = 34 \, cm^2/s$$



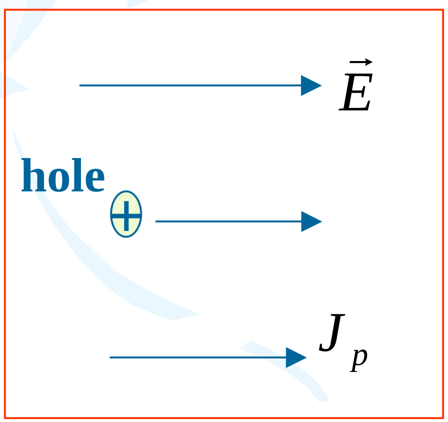


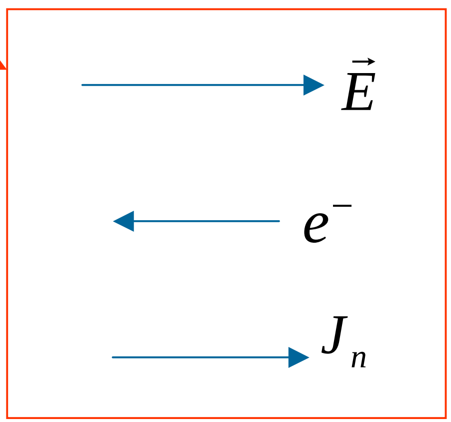
The conventional current direction is the positive charge flow direction

Currents in semi-conductor = drift current + diffusion current

$$J_p = pq\mu_p E - qD_p \frac{dp}{dx}$$

$$J_n = nq\mu_n E + qD_n \frac{dn}{dx}$$





Einstein relationship : relationship between drift current and diffusion current

$$\boxed{\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T}$$

V_T thermal voltage

溫度伏特當量

At room temperature $(20^o C) V_T \approx 25mV$

$$V_T \equiv \frac{kT}{q}$$

Boltzmann's constant

$$k = 1.38 \times 10^{-23}\ {}^{joules}\!/\!_{kelvin}$$

$$T = 273 + {}^o C$$

$$q = 1.6 \times 10^{-19}\ coulomb$$

$$T = 20^o C \rightarrow 293^o K \Rightarrow V_T \approx 25mV$$

$$T = 27^o C \rightarrow 300^o K \Rightarrow V_T \approx 26mV$$

Current in solid-state material

- Insulator

$$J_T = 0$$

- Semi-conductor

$$J_T = J_p + J_n$$

$$J_p = pq\mu_p E - qD_p \frac{dp}{dx}$$

$$J_n = nq\mu_n E + qD_n \frac{dn}{dx}$$

- Conductor

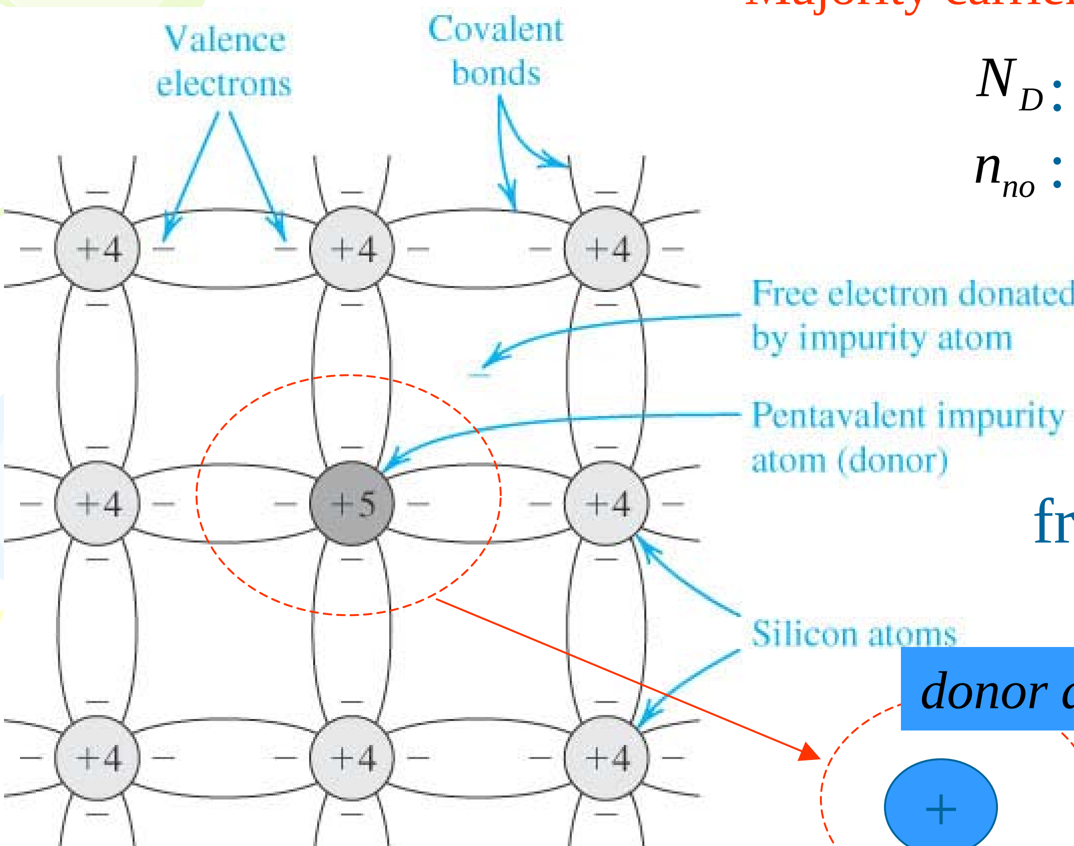
$$J_T = J_n = nq\mu_n E$$

N-type impure semiconductor (donor)

Majority carriers are negative charges : electrons

N_D: Donor atoms concentration

n_{no} : free electrons concentration



In thermal equilibrium

$$\boxed{n_{no} \approx N_D}$$

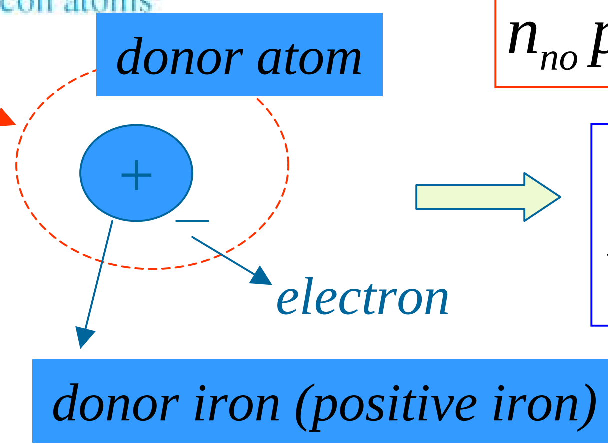
n-type

from semiconductor physic

Mass-action law

$$\boxed{n_{no}\, p_{no} = n_i^2}$$

$$\boxed{p_{no} \approx \frac{n_i^2}{N_D}}$$



Doped +5 atoms: Sb, P, As

銻,磷,砷

P-type impure semiconductor (acceptor)

Majority carriers are positive charges : holes

N_A : Acceptor atoms concentration

p_{po} : free holes concentration

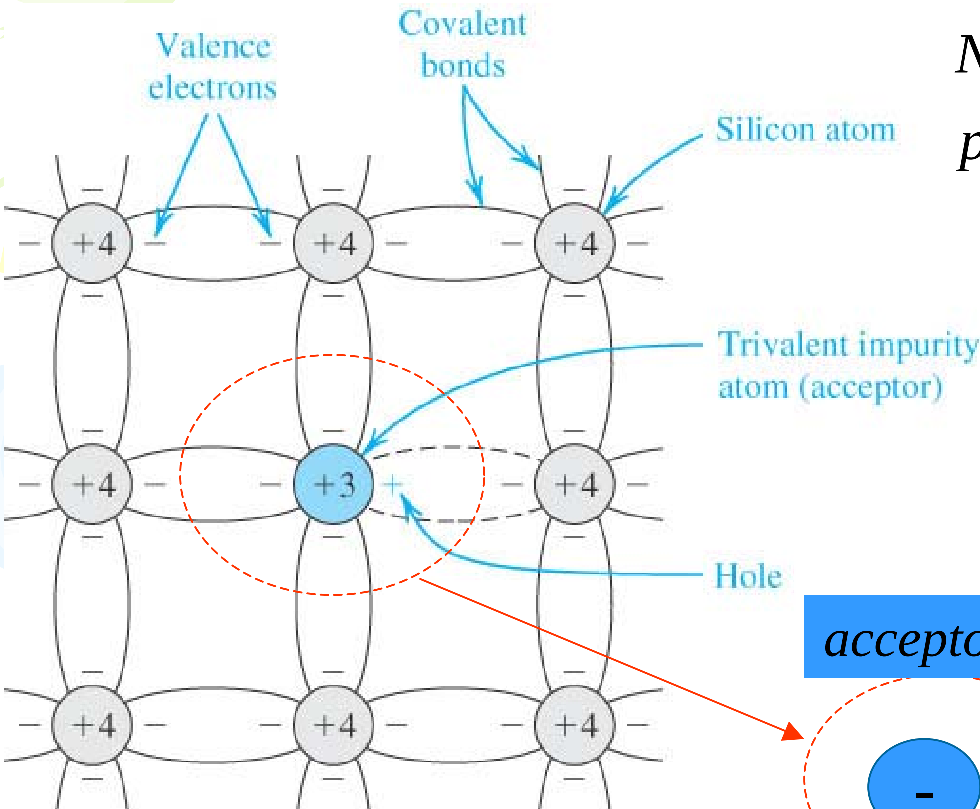
In thermal equilibrium

$$\boxed{p_{po} \approx N_A}$$

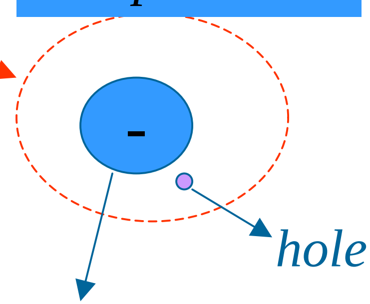
from semiconductor physic

$$p_{po} n_{po} = n_i^2$$

$$\boxed{n_{po} \approx \frac{n_i^2}{N_A}}$$



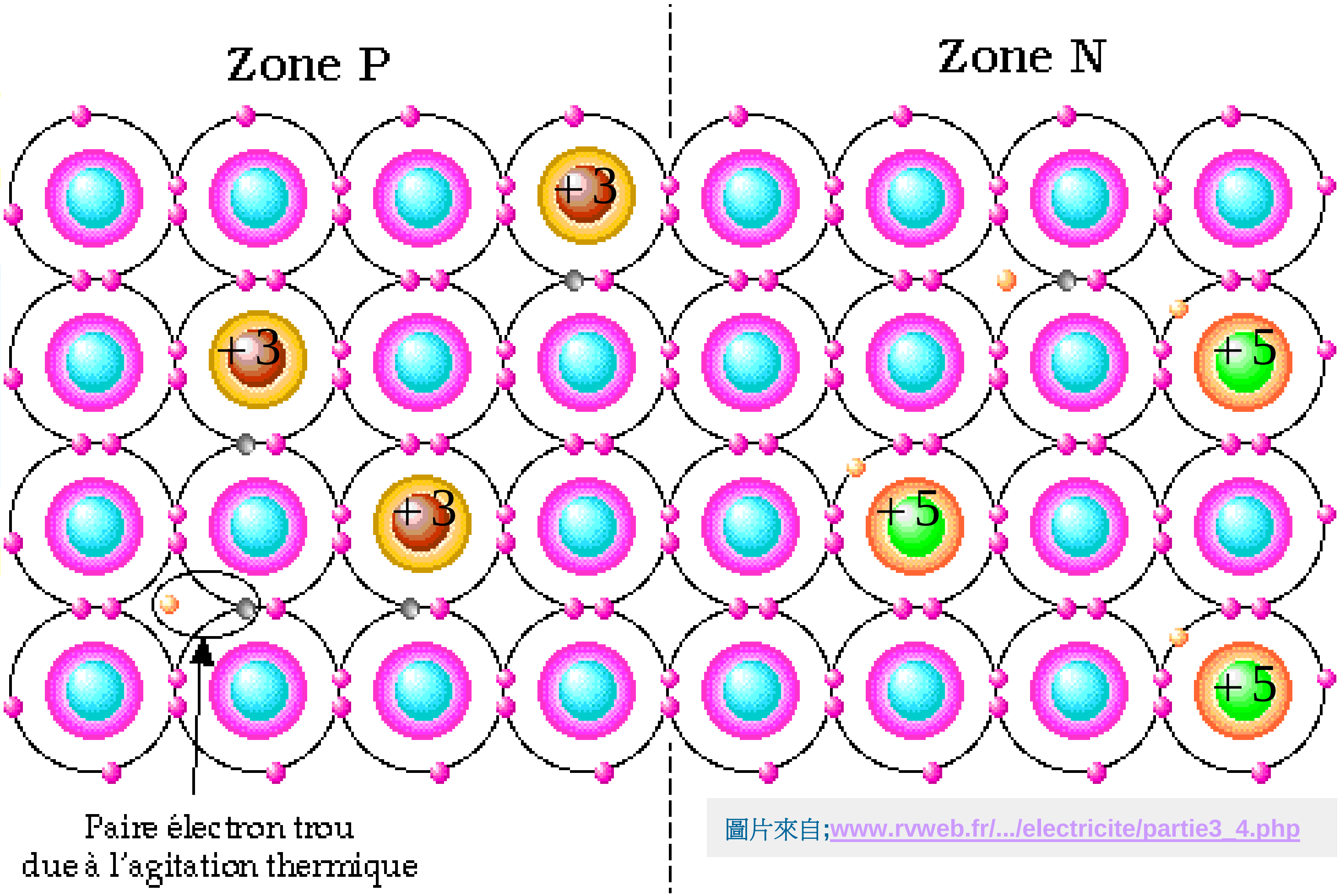
acceptor atom



acceptor iron (negative iron)

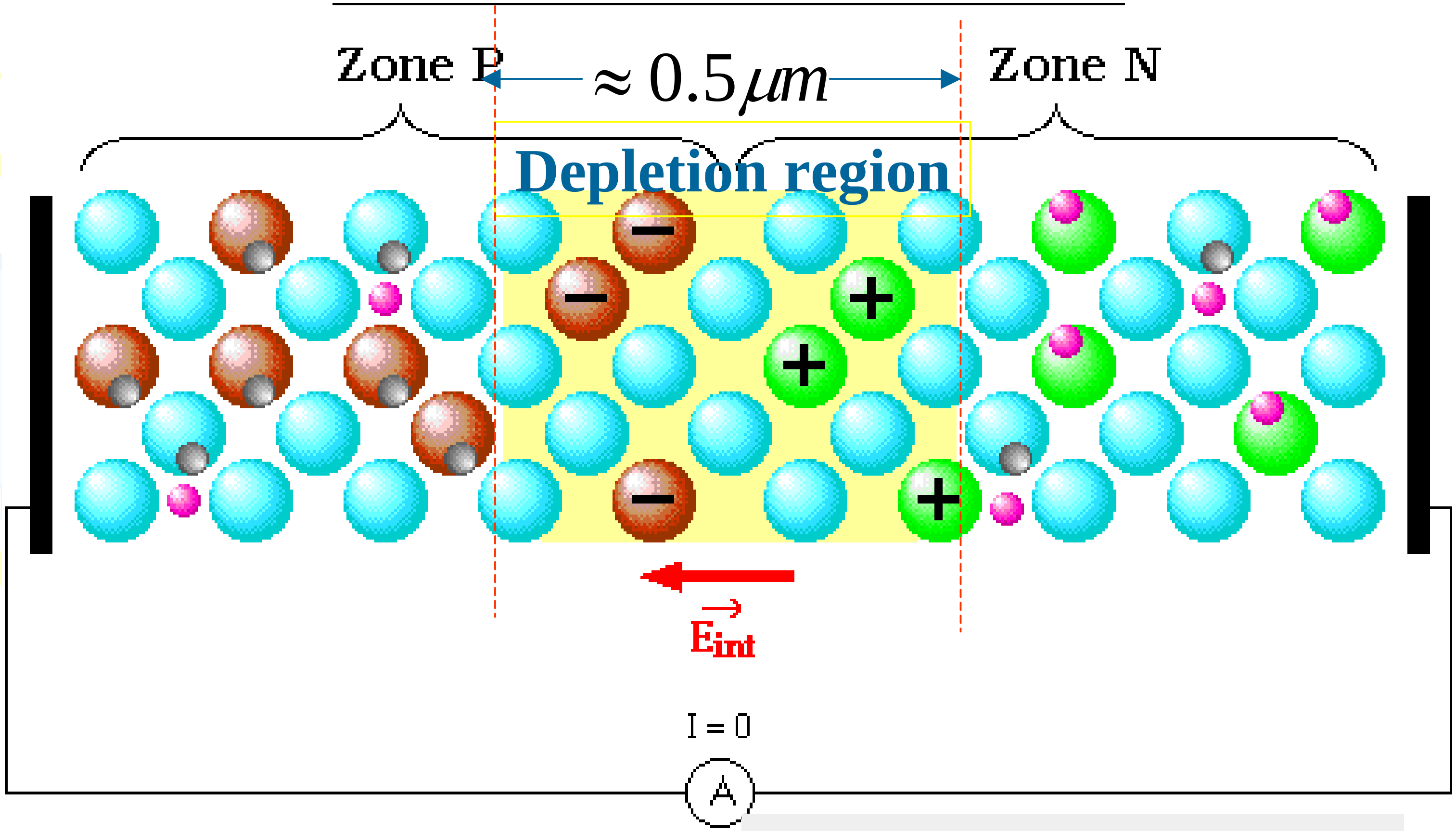
Doped +3 atoms: B, Ga, In,
硼,鎵,銦

Jonction PN



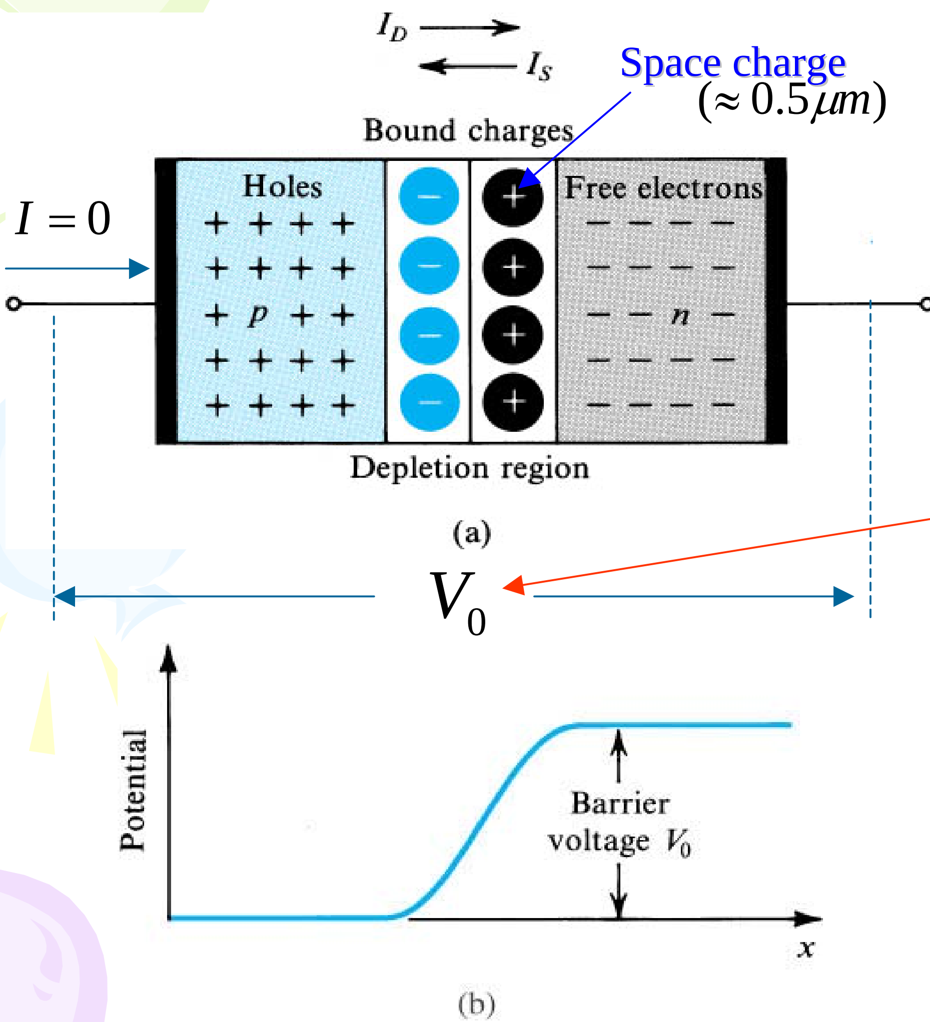
圖片來自;www.rvweb.fr/.../electricite/partie3_4.php

Jonction PN sans champ extérieur



圖片來自;www.rvweb.fr/.../electricite/partie3_4.php

PN Junction under open-circuit



I_D : Diffusion current

I_S : Drift current

$$\boxed{\therefore I = 0 \rightarrow I_D = I_S}$$

Contact difference of potential

$$\boxed{V_o = V_T \ln(\frac{N_A N_D}{n_i^2})}$$

For silicon at room temperature

$$\boxed{V_o = 0.6 \sim 0.8V}$$

$$J_p = pq\mu_p E - qD_p \frac{dp}{dx}$$

$$J_n = nq\mu_n E + qD_n \frac{dn}{dx}$$

$$J_p = 0 \Rightarrow pq\mu_p E = qD_p \frac{dp}{dx}$$

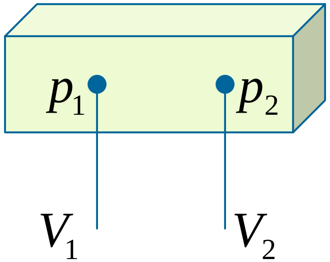
$$E = \frac{D_p}{p\mu_p} \frac{dp}{dx}$$

$$\because \frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T$$

$$\Rightarrow E = \frac{V_T}{p} \frac{dp}{dx}$$

$$\because E = -\frac{dV}{dx}$$

$$\Rightarrow dV = -V_T \frac{dp}{p}$$



$$\int dV = \int -V_T \frac{1}{p} dp$$

$$\to V_2 - V_1 = -V_T(\ln p_2 - \ln p_1) = V_T \ln \frac{p_1}{p_2}$$

Boltzmann equation

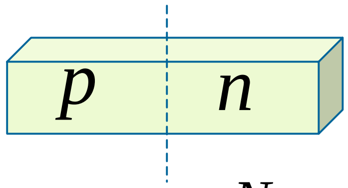
$$\Rightarrow p_1 = p_2 e^{\frac{V_{21}}{V_T}}$$

$$J_n = 0 \Rightarrow n_1 = n_2 e^{\frac{-V_{21}}{V_T}}$$

Mass-action law

$$n_1 p_1 = n_2 p_2 = n_i^2$$

$$V_o = V_{21} = V_T \ln \frac{p_1}{p_2}$$

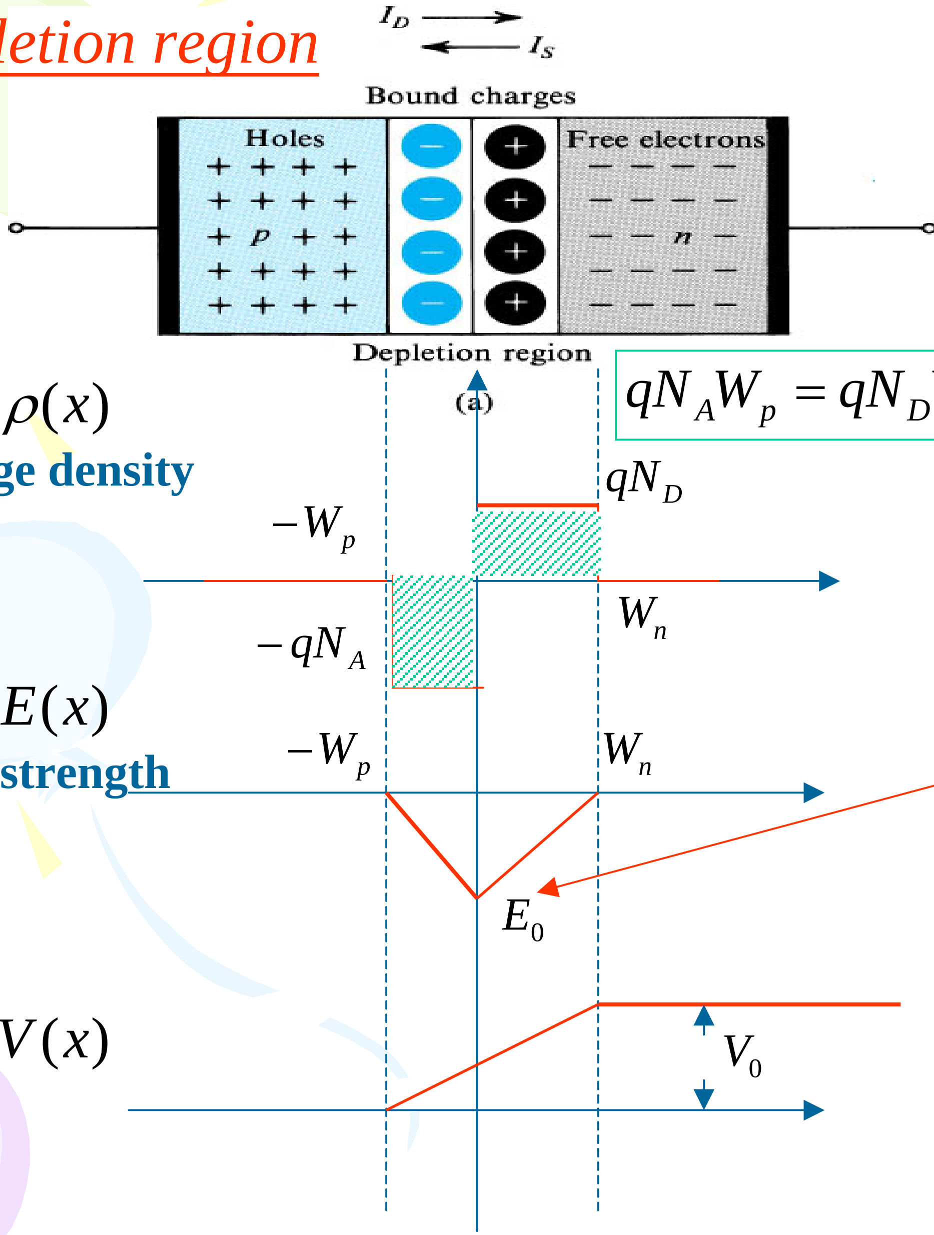


$$p_1 = p_{po} = N_A$$

$$p_2 = p_{n0} = n_i^2 / N_D$$

$$\boxed{V_o = V_T \ln \frac{N_A N_D}{n_i^2}}$$

Depletion region



$\rho(x)$
Charge density

$$qN_A W_p = qN_D W_n$$

$E(x)$
Field strength

$V(x)$

Poisson equation

$$\nabla^2 V = -\frac{\rho}{\varepsilon}$$

$$\Rightarrow \frac{\partial^2 V}{\partial x^2} = -\frac{\rho(x)}{\varepsilon}$$

$$E(x) = \int_{-W_p}^{W_n} \frac{\rho(x)}{\varepsilon} dx$$

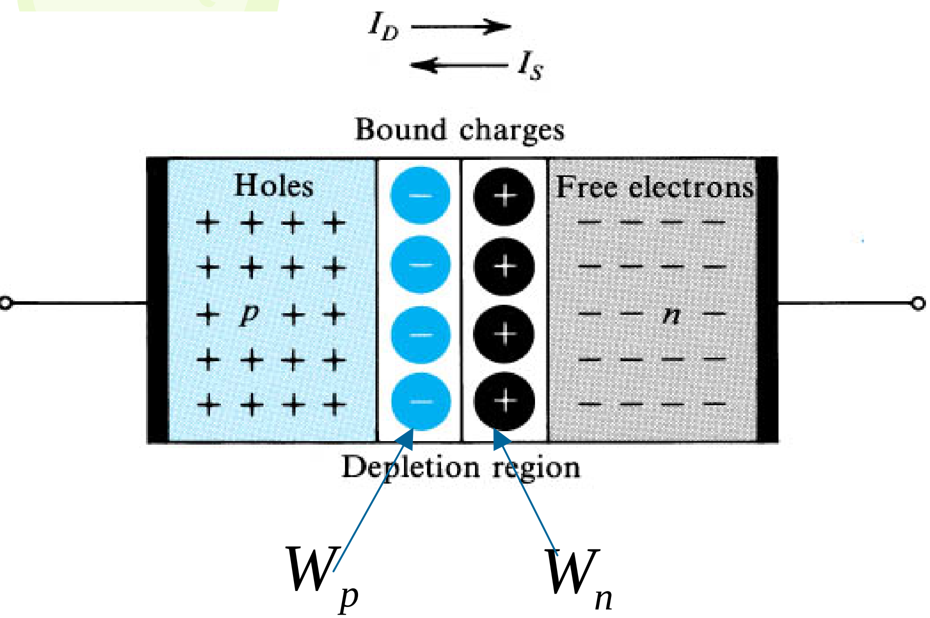
$$V(x) = -\int_{-W_p}^{W_n} E(x) dx$$

$$\boxed{E_0 = -\frac{qN_A W_p}{\varepsilon} = -\frac{qN_D W_n}{\varepsilon}}$$

$$V_0 = -\int_{-W_p}^{0} E(x)dx - \int_{0}^{W_n} E(x)dx$$

$$= \frac{qN_A W_p^2}{2\varepsilon} + \frac{qN_D W_n^2}{2\varepsilon}$$

Depletion width



Charge equality

$$qW_pAN_A = qW_nAN_D$$

$$\Rightarrow \frac{W_n}{W_p} = \frac{N_A}{N_D}$$

$$\Rightarrow W_nN_D = W_pN_A$$

$$W = W_p + W_n \Rightarrow W = \frac{N_D}{N_A}W_n + W_n$$

$$\Rightarrow W_n = \frac{N_A}{N_A + N_D}W \Rightarrow W_p = \frac{N_D}{N_A + N_D}W$$

$$V_0 = \frac{qN_AW_p^2}{2\varepsilon} + \frac{qN_DW_n^2}{2\varepsilon}$$

$$V_0 = \frac{q}{2\varepsilon}\left(\frac{N_AN_D}{N_A + N_D}\right)W^2$$

$$\boxed{W_{dep} = W_n + W_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}}$$

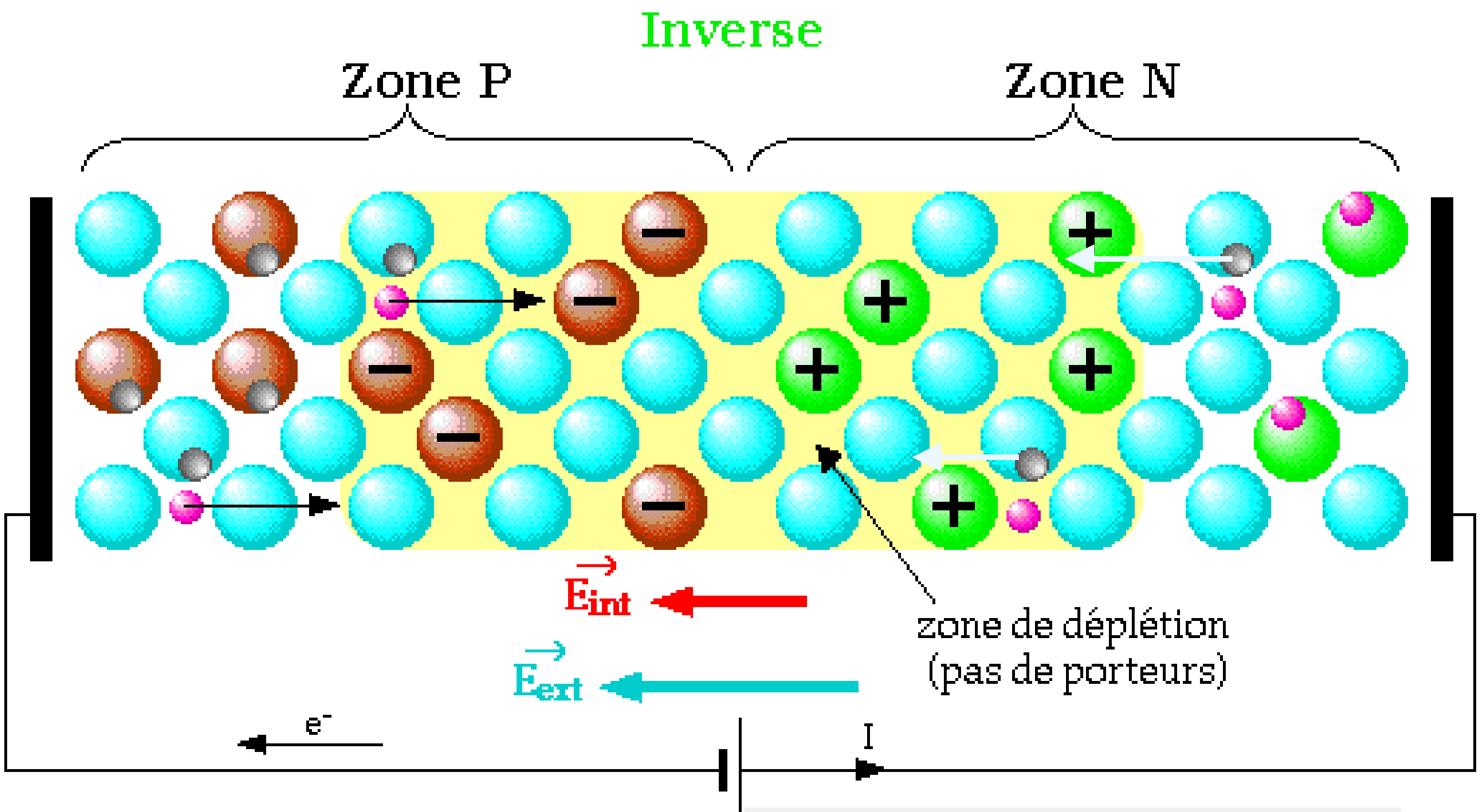
ε_s : Silicon Electrical permirrivity 容電係數

For silicon

$$\varepsilon_s = 1.04 \times 10^{-12} \, F/cm$$

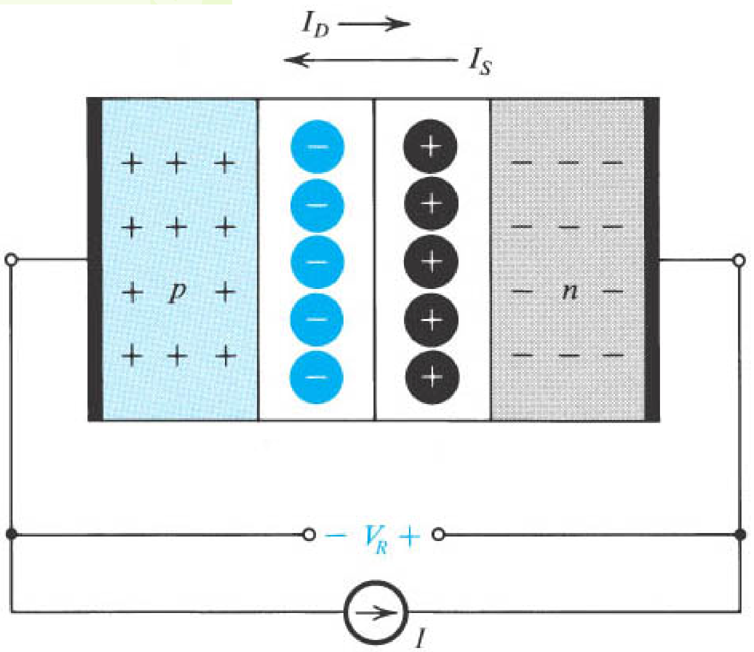
$$W_{dep} = 0.1\mu m \sim 1\mu m$$

Jonction PN avec champ extérieur



圖片來自;www.rvweb.fr/.../electricite/partie3_4.php

PN Junction reverse bias



$$I_S > I_D \qquad I_S - I_D = I$$

$$q_J = q_N = qN_D W_n A$$

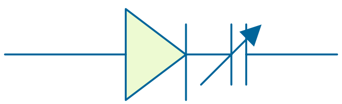
$$q_J = q\frac{N_A N_D}{N_A + N_D} A W_{dep}$$

$$\boxed{W_{dep} = W_n + W_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}}$$

Junction capacitance

$$C_j = \frac{C_{jo}}{\sqrt{1 + \frac{V_R}{V_o}}}$$

varactor



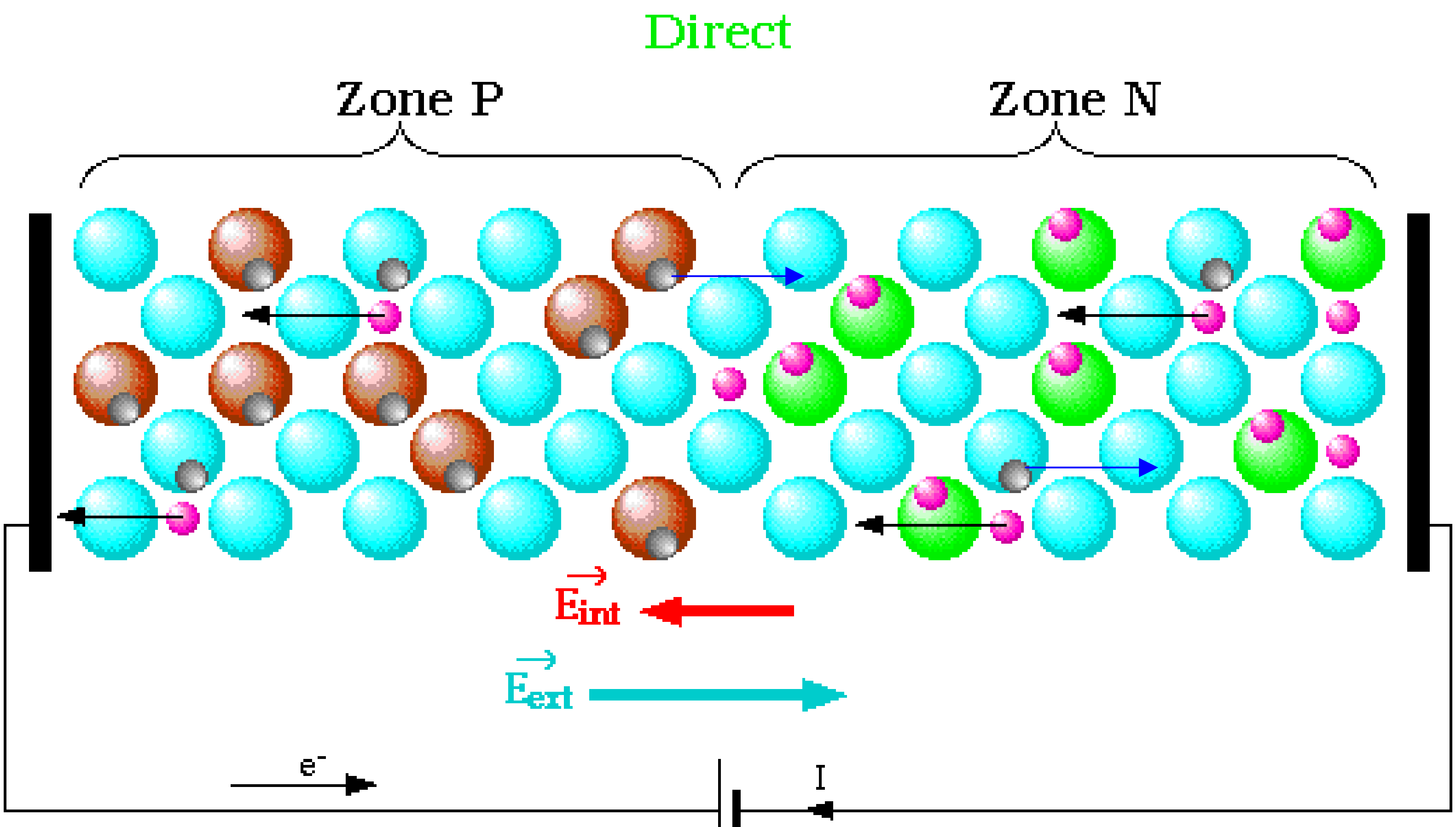
$$C_j = \left.\frac{dq_J}{dV_R}\right|_{V_R = V_Q}$$

$$\Rightarrow C_j = \frac{\varepsilon_s A}{W_{dep}}$$

$$V_R = 0$$

$$\boxed{C_{jo} = A\sqrt{\frac{q\varepsilon_s}{2}\left(\frac{N_A N_D}{N_A + N_D}\right)\frac{1}{V_0}}}$$

Jonction PN
avec champ extérieur



圖片來自;www.rvweb.fr/.../electricite/partie3_4.php

Minority carriers distribution in forward bias (the story about reverse saturation current)

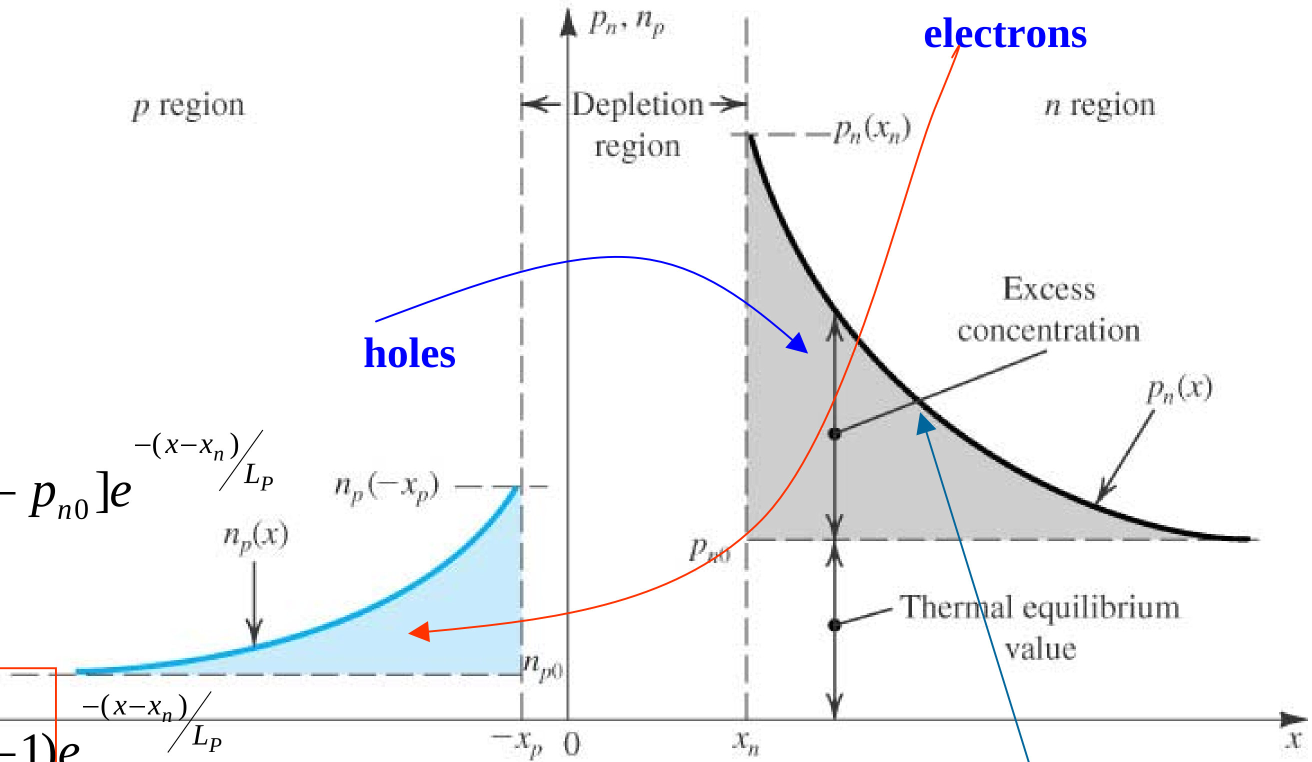
$$p_1 = p_2 e^{\frac{V_{21}}{V_T}}$$ **page18**

$$\rightarrow p_n(x_n) = p_{n0} e^{\frac{V}{V_T}}$$

$$p_n(x) = p_{n0} + [p_n(x_n) - p_{n0}] e^{-(x-x_n)/L_P}$$

$$\because J_p = -qD_P \frac{dp}{dx}$$

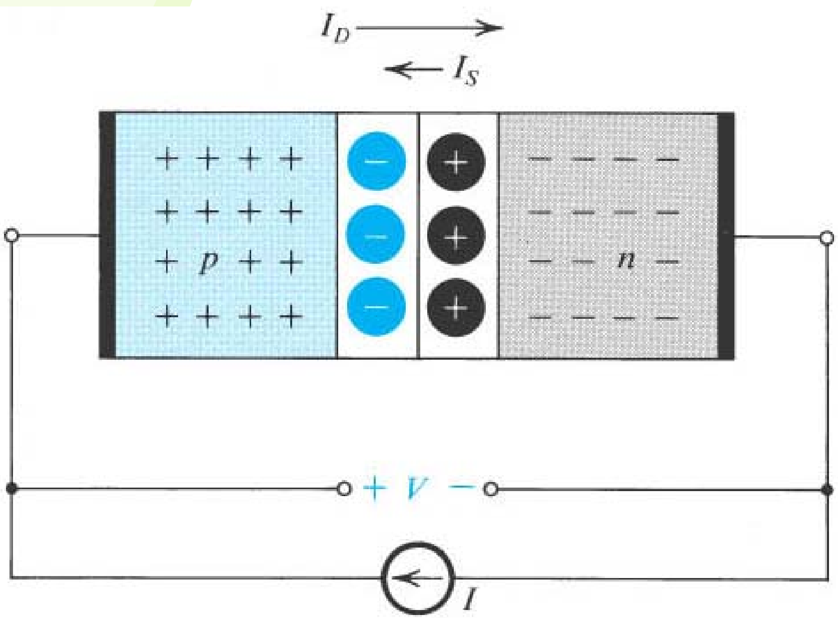
$$\Rightarrow J_p = \boxed{q \frac{D_p}{L_p} p_{n0}(e^{\frac{V}{V_T}} - 1)} e^{-(x-x_n)/L_P}$$



Total loss by recombination
= External electric field inject electrons

Inject holes from P region to diffuse away from the junction into the N region and disappear by recombination

PN Junction under forward bias



$$J_p = q\frac{D_p}{L_p}p_{no}(e^{V/V_T}-1)$$

$$J_n = q\frac{D_n}{L_n}n_{po}(e^{V/V_T}-1)$$

$$I = A(J_p + J_n)$$

$$I = \boxed{Aqn_i^2(\frac{D_p}{L_pN_D}+\frac{D_p}{L_pN_D})}(e^{V/V_T}-1)$$

$$\boxed{I_S < I_D}$$

Reverse saturation current

$$I_s = Aqn_i^2(\frac{D_n}{L_nN_A}+\frac{D_p}{L_pN_D})$$

$$I = I_s(e^{V/V_T}-1)$$

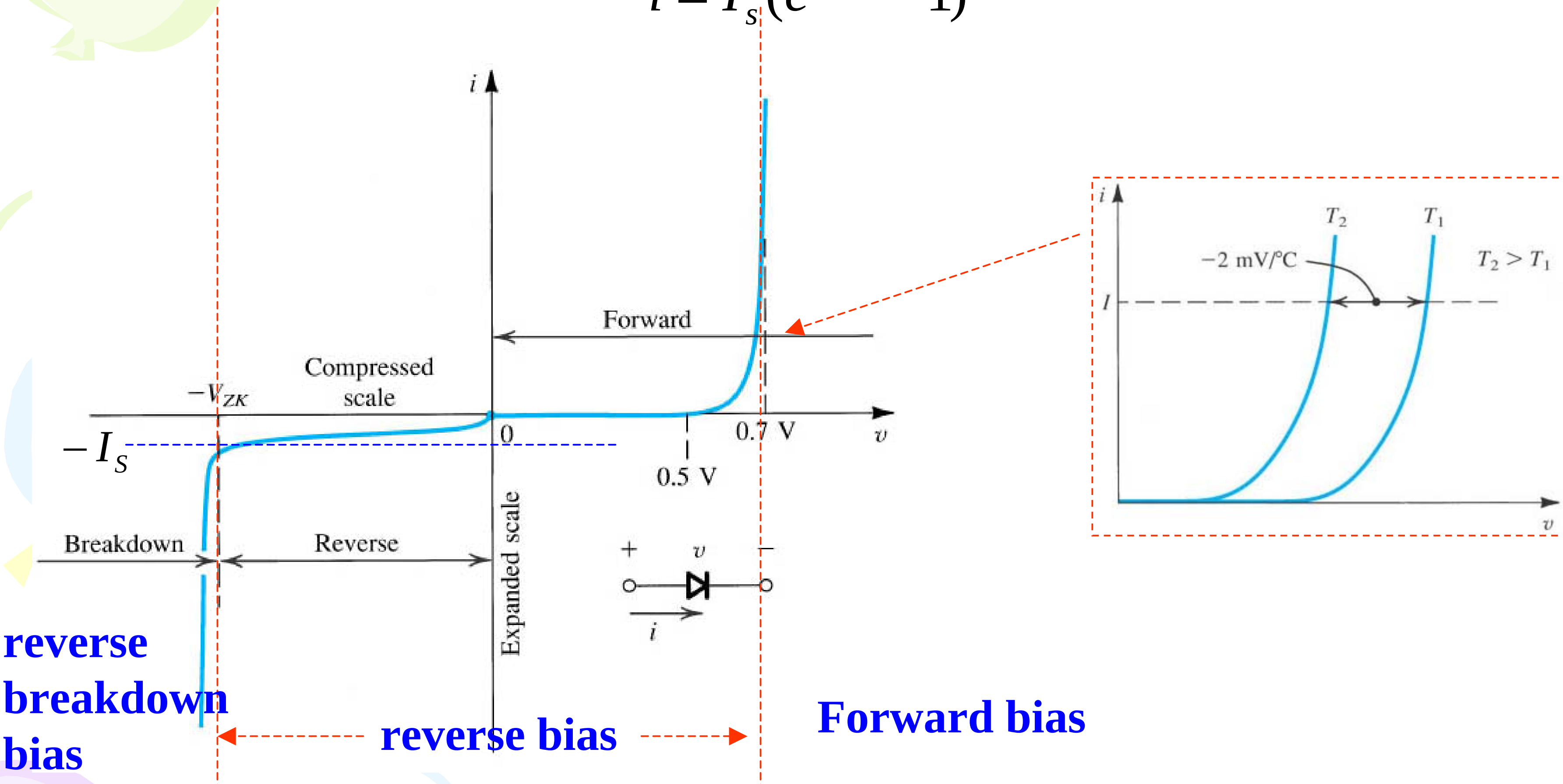
0

$$\boxed{if \quad V << 0}$$

$$\boxed{I = I_s(e^{V/V_T}-1)}$$

Diode's *i-v* relationship

$$i = I_s\left(e^{v/nV_T} - 1\right)$$



$n = 1,2$ Ideality factor which depending on diode's material and physical structure

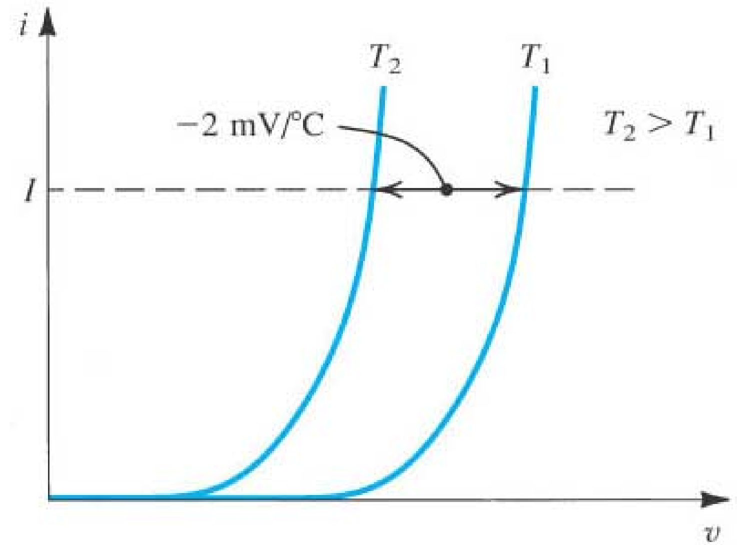
Forward bias

$$i = I_s\left(e^{v/nV_T} - 1\right)$$

$$i \gg I_s \longrightarrow$$ Forward

$$\Rightarrow i \approx I_s e^{v/nV_T}$$

$$\Rightarrow v = nV_T \ln\frac{i}{I_s}$$



n : Ideality factor which depending on diode's material and physical structure

$$\boxed{n = \begin{cases} 1 & Ge \\ 1 & Si(I_D \ge 25mA) \\ 2 & Si(I_D \le 25mA) \end{cases}}$$

$$I_1 \approx I_s e^{V_1/nV_T}$$

$$I_2 \approx I_s e^{V_2/nV_T}$$

$$\Rightarrow V_2 - V_1 = nV_T \ln\frac{I_2}{I_1} = 2.3nV_T \log\frac{I_2}{I_1}$$

Open current $\longrightarrow$ $V_D = 0 \Rightarrow I_D = 0$

Forward bias $\longrightarrow$ $V_D > 0 \Rightarrow I_D \approx I_s e^{\frac{V_D}{nV_T}}$

reverse bias $\longrightarrow$ $V_D < 0 \Rightarrow I_D = -I_s$

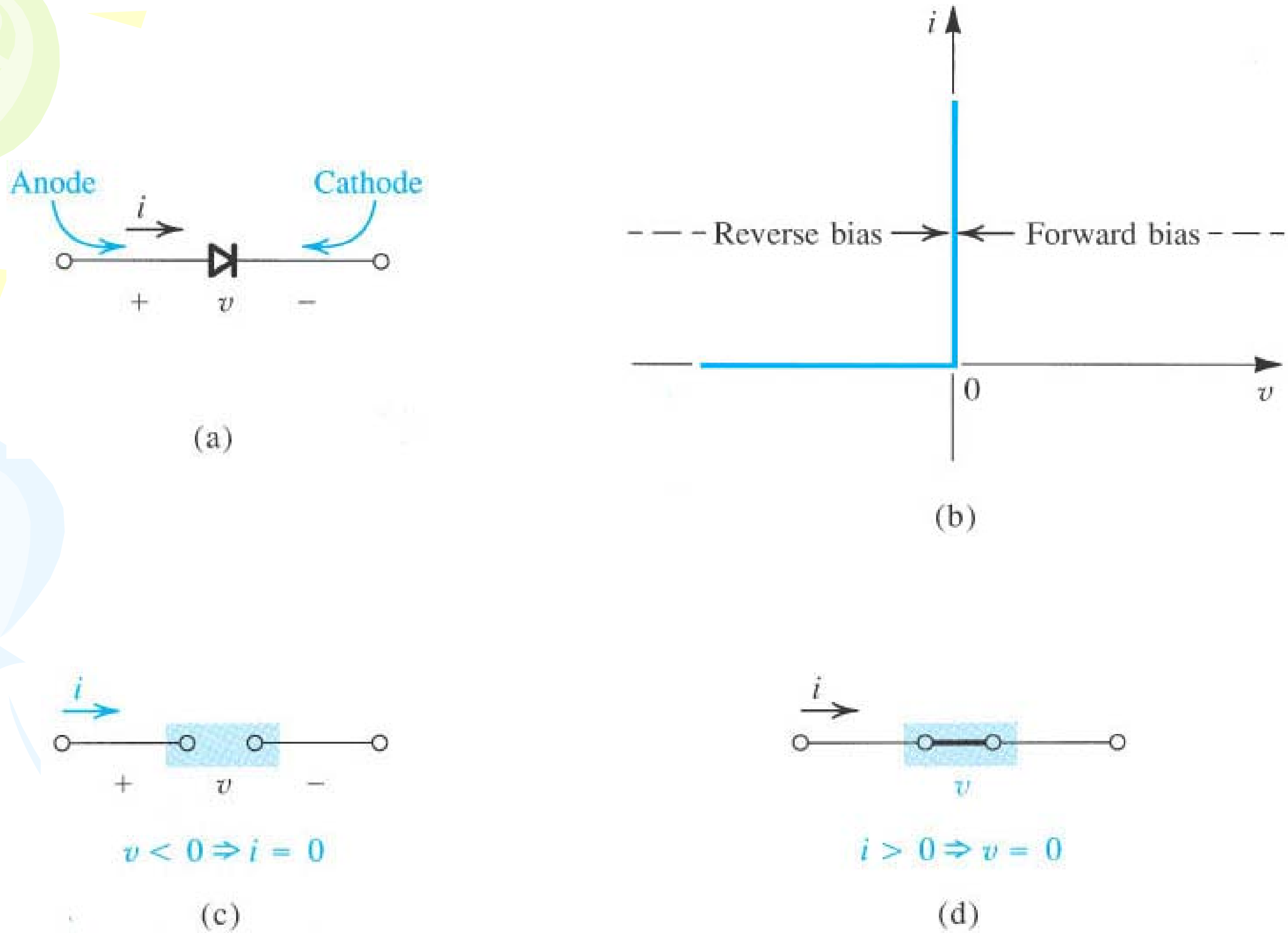
Cut-in voltage V_r

$$V_r = 0.7 \rightarrow \qquad Si$$

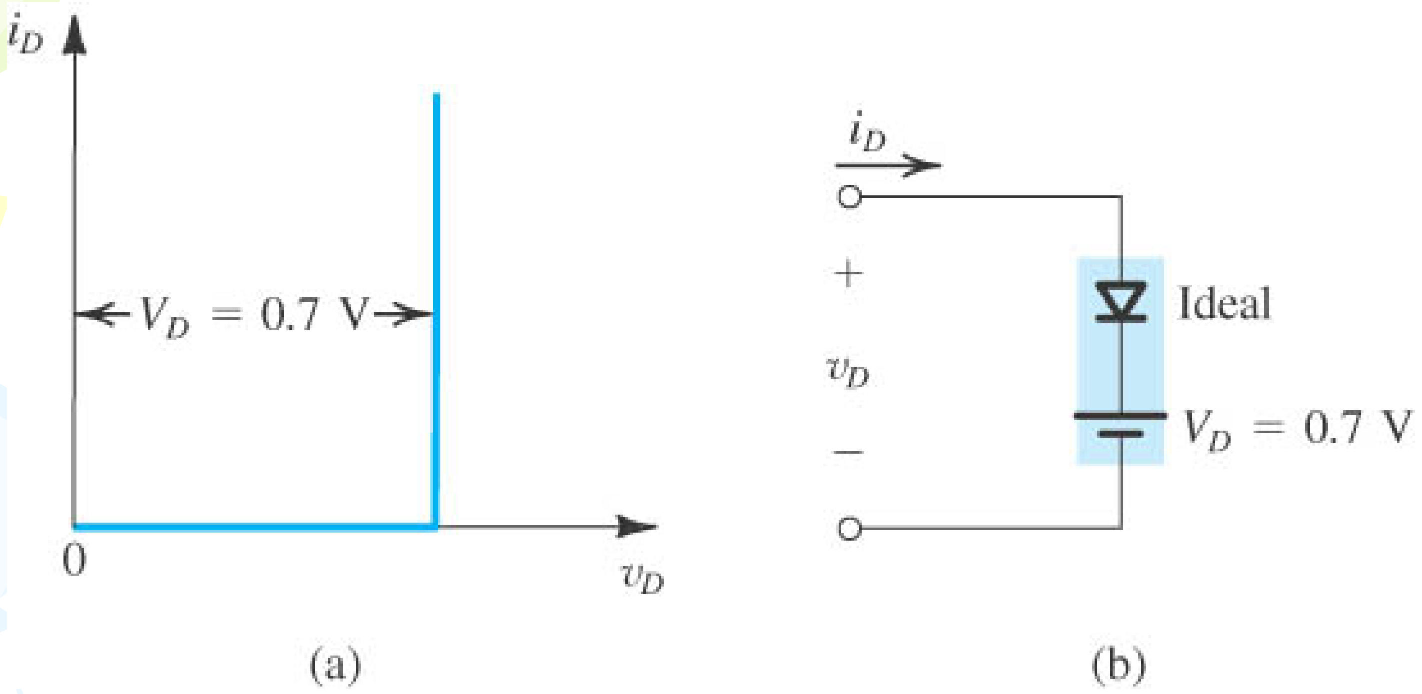
$$V_r = 0.25 \rightarrow \qquad Ge$$

$$V_r = 1.2 \rightarrow \qquad GaAs$$

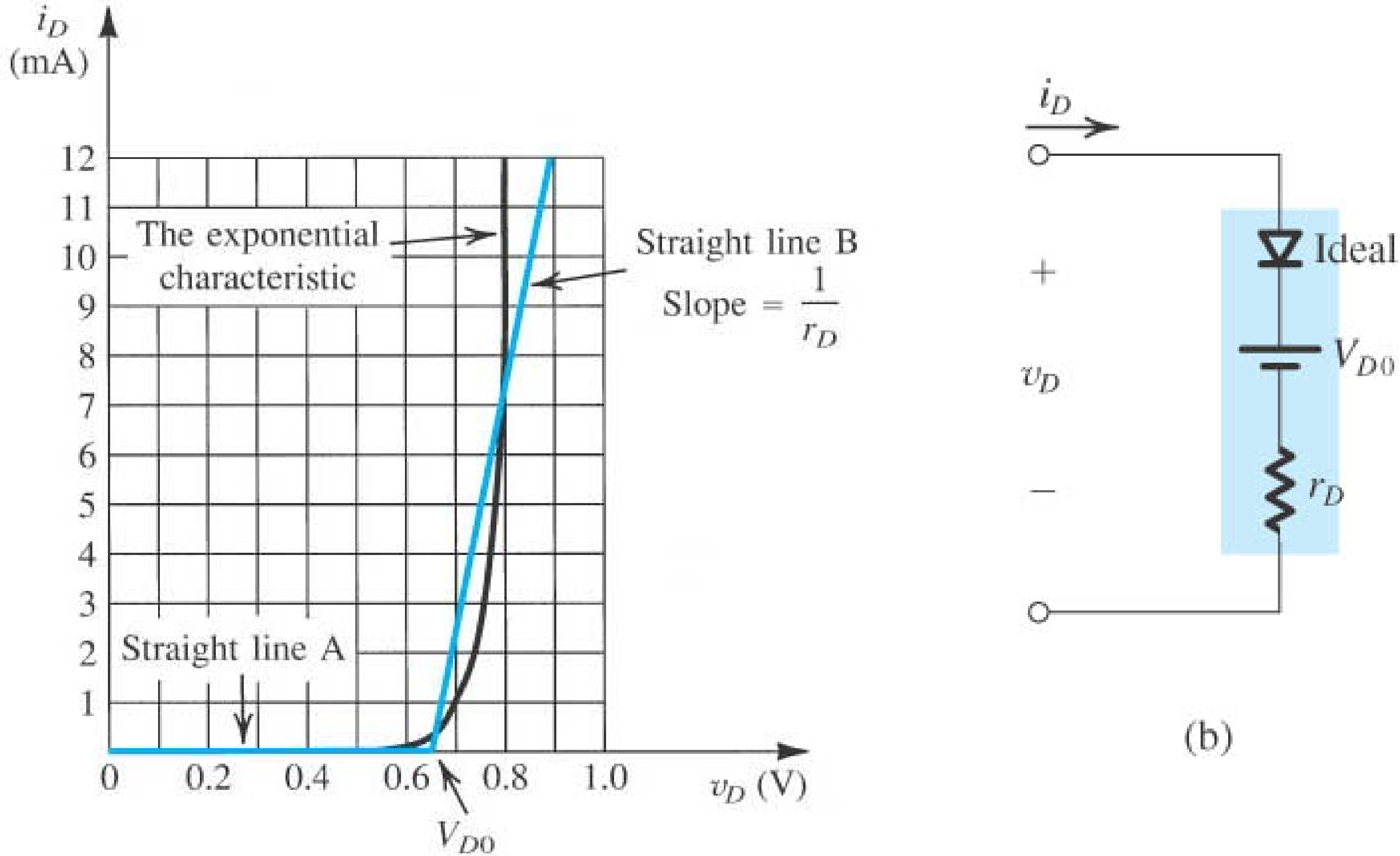
Diode Model I (ideal model)



Diode Model II (constant-Voltage Drop model)



Diode Model III (Piecewise-linear model)



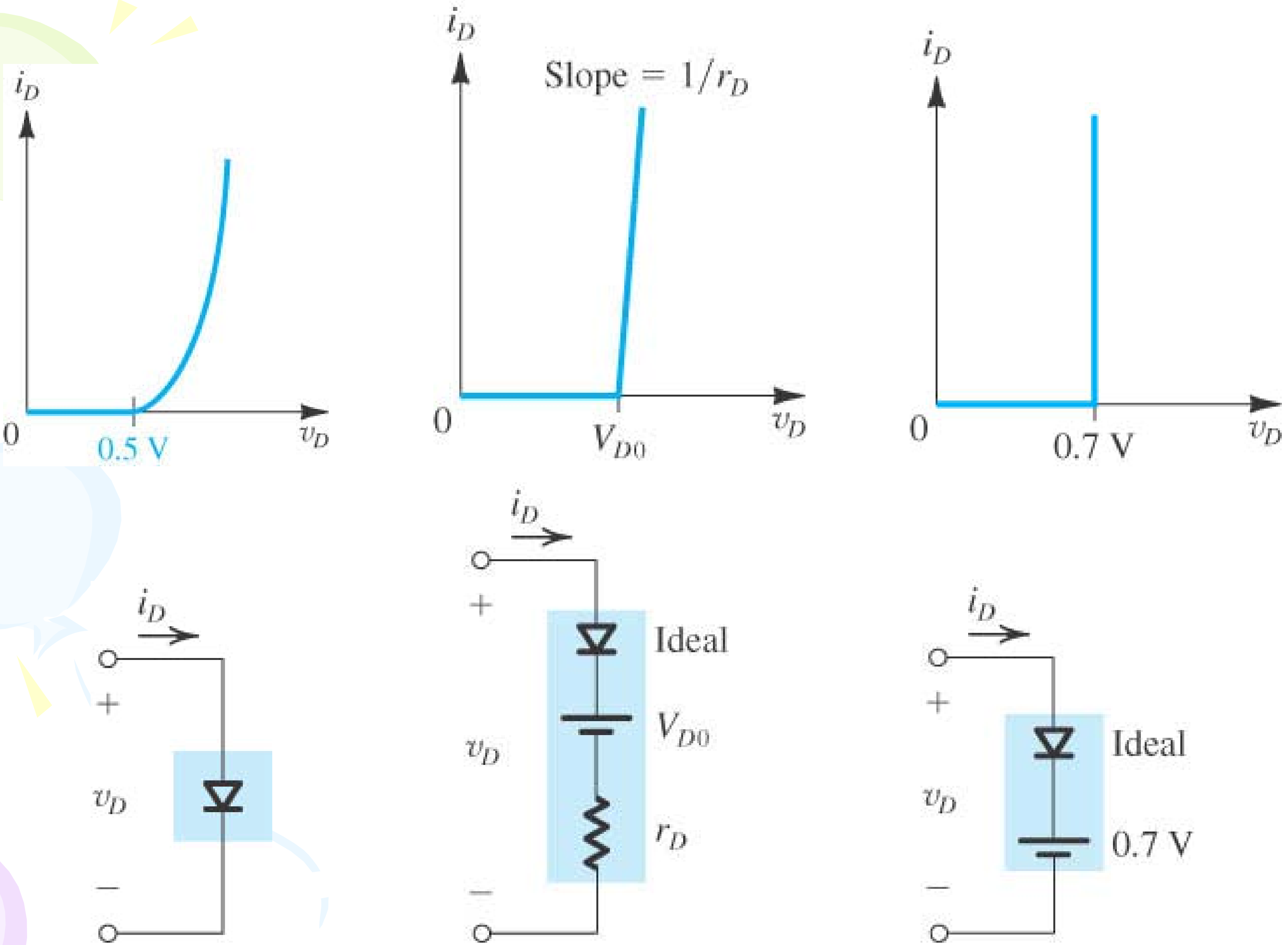
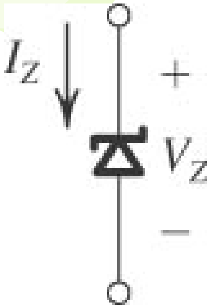
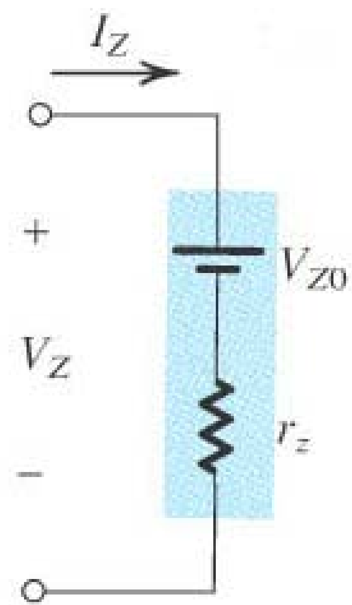
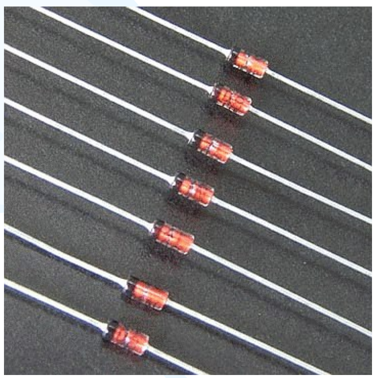


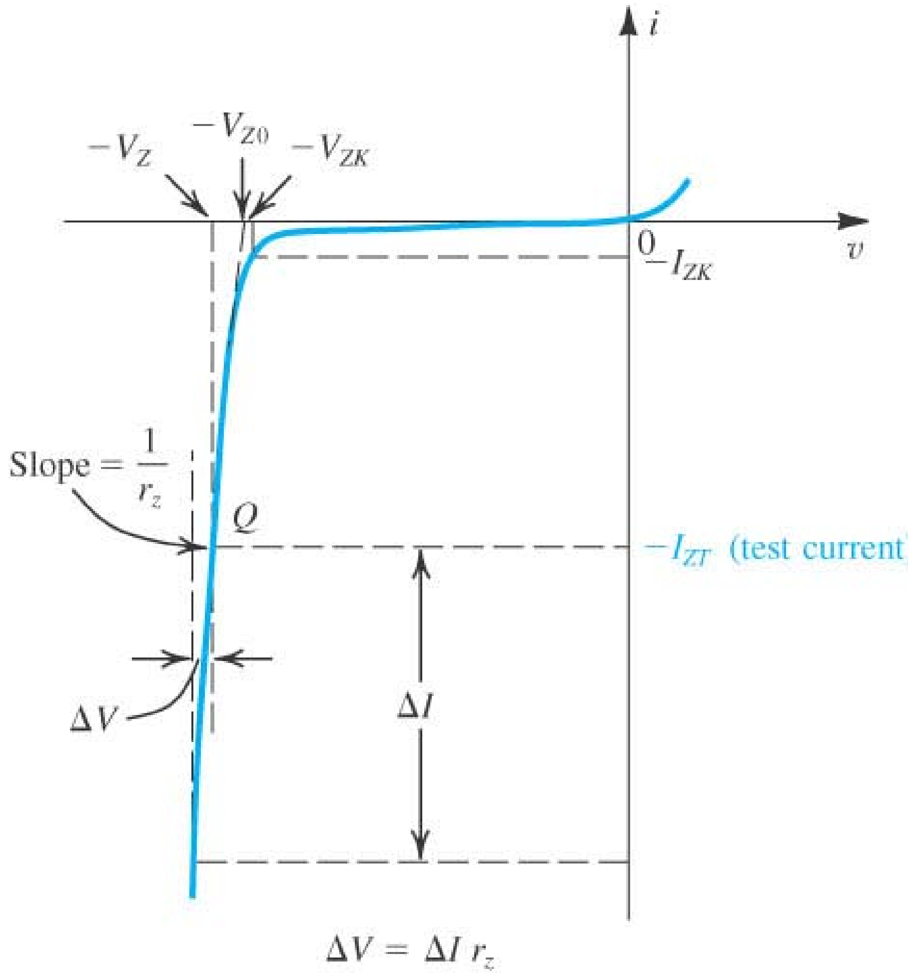
Table 3.1 Modeling the Diode Forward Characteristic

Special Diodes (Zener Diode)

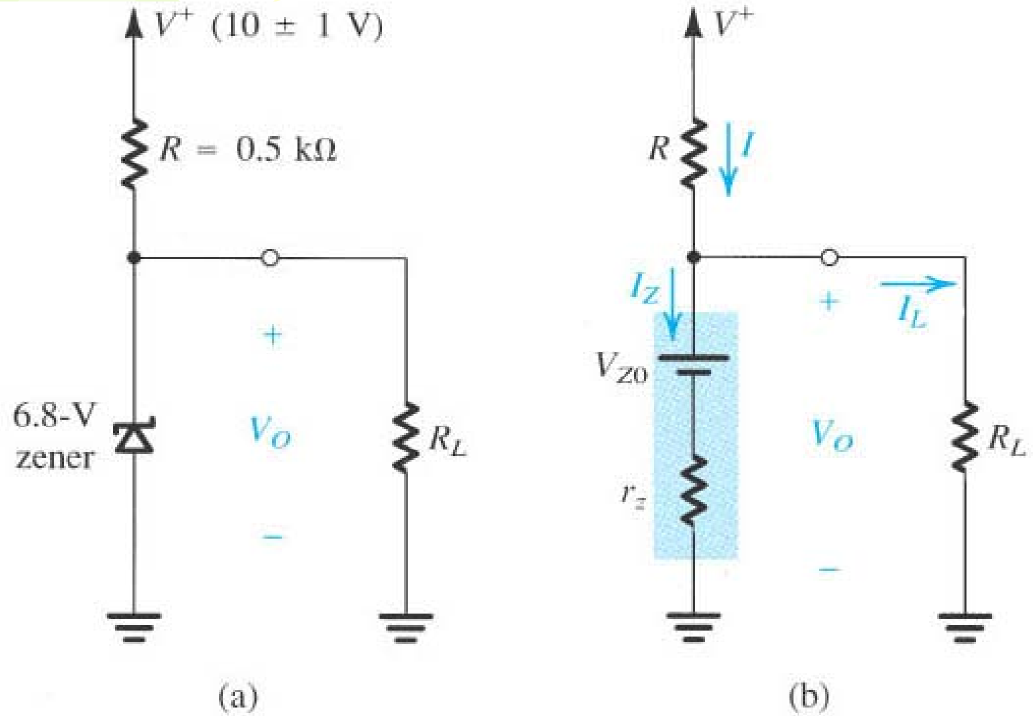








圖片來自;www.alibaba.com/catalog/11418809/0_5w_Series



$$I = I_z + I_L$$

$$\Rightarrow \frac{V - V_z}{R} = \frac{P_z}{V_z} + \frac{V_z}{R_L}$$

$$\boxed{\begin{aligned} I &= I_{z(\max)} + I_{L(\min)} \\ \Rightarrow \frac{V - V_z}{R} &= \frac{P_{z(\max)}}{V_z} + \frac{V_z}{R_{L(\max)}} \end{aligned}}$$

$$\boxed{\begin{aligned} I &= I_{z(\min)} + I_{L(\max)} \\ \Rightarrow \frac{V - V_z}{R} &= \frac{P_{z(\min)}}{V_z} + \frac{V_z}{R_{L(\min)}} \end{aligned}}$$

Ideal case: $\boxed{r_z = 0}$

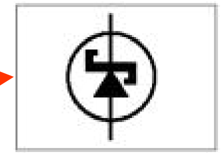
$$R_L \uparrow (\max) \rightarrow I_L \downarrow \because R = K \therefore I = \mathit{fixed} \Rightarrow I_z \uparrow (\max)$$

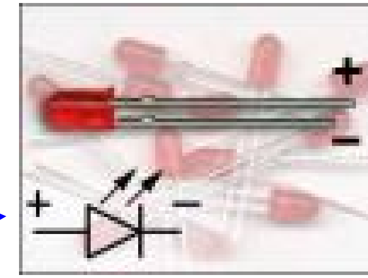
$$R_L \downarrow (\min) \rightarrow I_L \uparrow \because R = K \therefore I = \mathit{fixed} \Rightarrow I_z \downarrow (\min)$$

The others Special Diodes

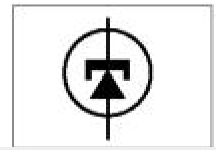
1. Schottky Diode
   - Metal + semiconductor (unipolar)
2. Light emitting diode (LED)
   - GaAs diode
   - GaN diode (B, G)
3. Tunnel diode
4. Photo diode (PD)
5. Opto coupler (LED + PD)

hyperphysics.phy-astr.gsu.edu/.../schottky.gif



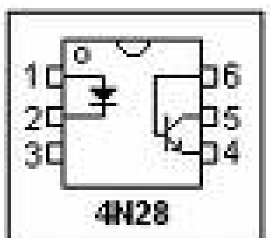


www.personeel.glr.nl/koster/elektro/ledjes.JPG

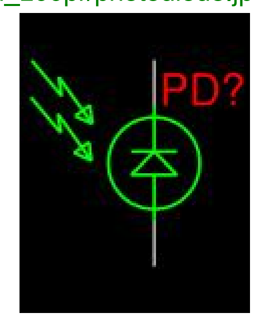


hyperphysics.phy-astr.gsu.edu/.../tundio.html

home.swipnet.se/.../hifi_100pr/photodiode.jpg



www.du.edu/~etuttle/electron/circ43.gif



www.geda.seul.org/.../analog/photodiode-1_tn.png

LED

- 1963 Red
- 1993 Blue
- 1996 white